

# Comment on astrophysical consequences of a neutrinophilic 2HDM

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Several authors have pointed out that the scalar-mediated interaction of neutrinos in a neutrinophilic two-Higgs-doublet model ( $\nu$ 2HDM) can be as strong as electromagnetic interaction [1–3]. We show that the coupling constants of neutrino-scalar interaction are actually restricted to be  $y_i \lesssim 1.5 \times 10^{-3}$  by supernova neutrino observation, and further constrained to be  $y_i \lesssim 2.3 \times 10^{-4}$  by precision measurements of acoustic peaks of the cosmic microwave background. Based on the energy-loss argument for supernova cores, we derive a slightly more restrictive bound  $y_i \lesssim 3.5 \times 10^{-5}$ . Therefore, the  $\nu$ 2HDM has lost its spirit of explaining tiny Dirac neutrino masses while keeping neutrino Yukawa couplings of order one.

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The  $\nu$ 2HDM extends the standard model with three right-handed neutrinos and introduces exclusively for neutrinos an extra Higgs doublet  $\varphi$ , which acquires a small vacuum expectation value (vev)  $v_\varphi = 0.1$  eV. In this model, neutrinos are Dirac particles, and their mass matrix is given by  $M_\nu = Y_\nu v_\varphi$  with  $Y_\nu$  being neutrino Yukawa coupling matrix. A salient feature of the  $\nu$ 2HDM is that  $Y_\nu$  can be of order one even for sub-eV neutrino masses [1–3]. In the flavor basis where the charged-lepton Yukawa coupling matrix is diagonal, one can further take  $Y_\nu$  to be Hermitian by rotating right-handed neutrino fields in the flavor space. Hence the Yukawa interaction of neutrinos can be written as

$$-\mathcal{L}_Y = \sum_{\alpha, \beta=e}^{\tau} (Y_\nu)_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta \eta = \sum_{i=1}^3 y_i \bar{\nu}_i \nu_i \eta, \quad (1)$$

where  $V^\dagger Y_\nu V = \text{Diag}\{y_1, y_2, y_3\}$  with  $V$  being the neutrino mixing matrix, which relates neutrino mass eigenstates  $\nu_i$  to flavor eigenstates  $\nu_\alpha$ , and  $m_i = y_i v_\varphi$  (for  $i = 1, 2, 3$ ) are neutrino masses. Here  $\eta$  is a scalar boson arising from the neutral component of  $\varphi$ , and its mass is naturally around the vev of  $\varphi$ , i.e.,  $m_\eta \approx v_\varphi = 0.1$  eV. Some cosmological and astrophysical consequences of the neutrino interaction in Eq. (1) with  $y_i \sim \mathcal{O}(1)$  have been discussed in Refs. [1–3], however, the restrictive bounds on neutrino Yukawa couplings are unfortunately missed.

In fact, stringent bounds on the neutrino-Majoron interaction have been obtained in the literature by assuming a pseudoscalar coupling  $iy_i \bar{\nu}_i \gamma_5 \nu_i \chi$  with  $\chi$  being a pseudoscalar boson [4, 5]. One can show that those bounds apply as well to the scalar case in the relativistic limit, where small neutrino masses can be neglected. However, it should be noticed that the lepton-number-violating processes are forbidden in the  $\nu$ 2HDM.

The observation of neutrinos from Supernova 1987A requires that the mean free path of electron antineutrinos in the presence of cosmic background particles should be

larger than the supernova distance, i.e.,  $\lambda_{\bar{\nu}_e}^{-1} D \lesssim 1$  with  $D = 51.4$  kpc, in order to avoid significant reduction of neutrino flux [4]. The relevant processes are  $\bar{\nu}_e + \eta \rightarrow \bar{\nu}_e + \eta$ ,  $\bar{\nu}_e + \nu_e \rightarrow \eta + \eta$  and  $\bar{\nu}_e + \nu_\alpha \rightarrow \nu_e + \bar{\nu}_\alpha$  for  $\alpha = e, \mu, \tau$ . After removing the lepton-number-violating contributions from the Majoron model [4], one can obtain a restrictive bound on neutrino Yukawa couplings

$$y_i \lesssim 1.5 \times 10^{-3}. \quad (2)$$

If  $\eta$  bosons decay rapidly into neutrinos and are absent in the cosmic background, the bound will be weaker but on the same order of magnitude. Given  $v_\varphi = 0.1$  eV, neutrino Yukawa couplings are determined by neutrino masses  $y_i = m_i/v_\varphi$ , thus heavier neutrino mass eigenstates interact more strongly with the scalar boson. In the case of normal mass hierarchy, the bound in Eq. (2) may be slightly relaxed to  $y_i \lesssim 10^{-2}$ , because electron antineutrino possesses a small fraction of the heaviest mass eigenstate [6]. For the inverted mass hierarchy or nearly degenerate neutrino mass spectrum, however, the bound in Eq. (2) is still applicable.

As indicated by precision measurements of the acoustic peaks of the cosmic microwave background, neutrinos should be freely streaming around the time of photon decoupling  $T_{\gamma, \text{dec}} = 0.256$  eV in order to avoid the acoustic oscillations of the neutrino-scalar fluid [5]. At this moment, the neutrino temperature is  $T_{\nu, \text{dec}} = (4/11)^{1/3} T_{\gamma, \text{dec}} = 0.183$  eV. For the relevant two-body scattering processes  $\nu_i + \eta \rightarrow \nu_i + \eta$ ,  $\nu_i + \bar{\nu}_i \rightarrow \eta + \eta$  and  $\nu_i + \bar{\nu}_i \rightarrow \nu_j + \bar{\nu}_j$  via  $\eta$ -exchange, we can simply estimate the scattering rate as  $\Gamma_\nu \approx y_i^4 T_{\nu, \text{dec}}$  up to some numerical factors. The free-streaming argument requires  $\Gamma_\nu$  to be smaller than the cosmic expansion rate  $H_{\gamma, \text{dec}} = 100 \text{ km s}^{-1} \text{ Mpc}^{-1} (\Omega_M h^2)^{1/2} (z_{\text{dec}} + 1)^{3/2}$  with  $\Omega_M h^2 = 0.134$  being the cosmic matter density and  $z_{\text{dec}} = 1088$  the redshift at photon decoupling. Hence one can derive a more restrictive bound  $y_i \lesssim 1.1 \times 10^{-7}$  [5]. Taking account of the existing bound on Yukawa couplings in Eq. (2), one should increase  $v_\varphi$  by three orders of magnitude to guarantee sub-eV neutrino masses. Therefore, the mass of  $\eta$  is expected to be  $m_\eta \approx v_\varphi = 100$  eV, which is much larger than neutrino temperature

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at the time of photon decoupling. As a consequence,  $\eta$  bosons have already decayed into neutrinos, and the relevant process  $\nu_i + \bar{\nu}_i \rightarrow \nu_j + \bar{\nu}_j$  is mediated by a virtual  $\eta$  boson [6]. The scattering rate is modified to be  $\Gamma_\nu \approx y_i^4 T_{\nu,\text{dec}}^5 / m_\eta^4 \approx y_i^4 T_{\nu,\text{dec}}^5 / v_\varphi^4 = y_i^8 T_{\nu,\text{dec}}^5 / m_i^4$ , thus the true bound from the free-streaming argument is

$$y_i \lesssim 2.3 \times 10^{-4}, \quad (3)$$

for  $m_i \sim 0.1$  eV. Since the scattering rate is proportional to  $y_i^8$ , the neglected numerical factors are indeed unimportant for the bound in Eq. (3).

An important point is that  $\eta$  is massive enough to decay into neutrino-antineutrino pairs  $\eta \rightarrow \nu_i + \bar{\nu}_i$ . The lifetime in its rest frame is  $\tau_\eta = (3y_i^2 m_\eta / 16\pi)^{-1} \approx 1.1 \times 10^{-9}$  s, where  $y_i = 10^{-4}$  and  $m_\eta \approx v_\varphi = 1$  keV have been taken. Although  $\eta$  bosons can be copiously produced in the supernova core, one may expect that they will decay soon after production and thus cannot cause excessive energy losses. However, since the temperature in the cooling phase is sufficiently high  $T = 30$  MeV, the lifetime of thermal  $\eta$  bosons should be lengthened by a Lorentz factor  $E/m_\eta \approx 10^5$ . Consequently, the relativistic  $\eta$  bosons before decaying may have traveled a distance  $l_\eta \approx 3.3 \times 10^6$  cm, which is larger than the core radius  $R = 10$  km. But  $\eta$  bosons cannot freely propagate in the neutrino background, their mean free path can be estimated as  $\lambda_\eta = (y_i^4 T)^{-1} \approx 6.6 \times 10^3$  cm that is comparable to the mean free path of neutrinos in the case of standard neutral-current interaction. Thus  $\eta$  bosons behave like a new species of neutrinos and accelerate the energy transfer, which leads to the reduction of the cooling time or the duration of supernova neutrino burst. There are two possibilities to avoid the contradiction with the neutrino observation of Supernova 1987A [7]: (i) to increase the coupling ( $y_i > 10^{-4}$ ) such that  $\lambda_\eta$  becomes much smaller and the energy transfer by  $\eta$  bosons is negligible; (ii) to decrease the coupling ( $y_i < 10^{-4}$ ) such that  $\eta$  bosons have never been trapped and thermalized in the core. The first possibility is already excluded by the bound in Eq. (3), while the second one is subject to the constraint from standard energy-loss arguments.

The production of  $\eta$  bosons will be efficient via the bremsstrahlung process  $\nu_i + N \rightarrow \nu_i + N + \eta$  because of the high nucleon density. The emission rate should be proportional to the thermal average of  $\nu N$  scattering rate  $\sigma n_\nu n_B$  where  $\sigma$  is the  $\nu N$  collision cross section,  $n_\nu$  and  $n_B$  are respectively the neutrino and baryon number

densities. The energy of emitted  $\eta$  bosons is of order  $T$ . Put all together, we can get the volume emission rate

$$Q_\eta \approx 54 y_i^2 G_F^2 T^6 n_B \approx 2.4 y_i^2 \times 10^{42} \text{ erg cm}^{-3} \text{ s}^{-1}, \quad (4)$$

where  $\sigma = G_F^2 E^2$ ,  $T = 30$  MeV and  $n_B = \rho/m_N$  with  $\rho = 3.0 \times 10^{14} \text{ g cm}^{-3}$  have been assumed. Note that all the neutrinos have been taken to be relativistic and non-degenerate, which is an excellent approximation for  $\nu_\mu$  and  $\nu_\tau$ . For degenerate  $\nu_e$ , there will be a blocking factor that suppresses the scattering rate, which has been neglected in Eq. (4) for an order-of-magnitude estimate. The energy loss should be small so as not to shorten the neutrino burst, so we require the volume emission rate to be  $Q_\eta \lesssim 3.0 \times 10^{33} \text{ erg cm}^{-3} \text{ s}^{-1}$  and then obtain

$$y_i \lesssim 3.5 \times 10^{-5}. \quad (5)$$

As a matter of fact, there are additional contributions to the production of  $\eta$  bosons, such as  $\nu_i + e^- \rightarrow \nu_i + e^- + \eta$  and  $\nu_i + \bar{\nu}_i \rightarrow \eta + \eta$ . Hence the bound may be slightly stronger if all the contributions are included. One can then verify that the mean free path  $\lambda_\eta \sim 10^8$  cm is much larger than the core radius, which is consistent with the prerequisite that  $\eta$  bosons can escape from the core and carry away energies.

Based on the above discussions, one may take  $y_i = 10^{-5}$  and figure out the cross section of  $\nu_i + \bar{\nu}_i \rightarrow \nu_j + \bar{\nu}_j$  via  $\eta$ -exchange, and that via  $Z^0$ -exchange. It is straightforward to get  $\sigma_\eta \sim y_i^4 / E^2$  for the former case, while  $\sigma_Z \sim G_F^2 E^2$  for the latter, where  $E$  is the neutrino energy. In the neutrinosphere with a typical temperature  $T = 10$  MeV, we further obtain  $\sigma_\eta / \sigma_Z \approx y_i^4 / G_F^2 E^4 \approx 10^{-4}$  for  $y_i = 10^{-5}$  and  $E = 3T = 30$  MeV. Therefore, the scalar-mediated neutrino interaction is too weak to equilibrate supernova neutrinos of different species in the neutrinosphere and thus cannot wash out the collective effects in supernova neutrino oscillations [1].

In conclusion, if the astrophysical bounds on the scalar-mediated neutrino interaction are taken into account, the motivation for the  $\nu 2\text{HDM}$  becomes very weak in the sense that tiny Dirac neutrino masses cannot be explained by a small vev but large Yukawa couplings.

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